Performance of the High-Energy Single-Event Effects Test Facility (SEETF) at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL)

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***Abstract*—The performance of Michigan State University's Single-Event Effects Test Facility (SEETF) during its inaugural runs is evaluated. Beam profiles and other diagnostics are presented, and prospects for future development and testing are discussed.**

I. Introduction

THE difficulty of single-event testing for commercial parts in novel packaging technologies (flip-chip, lead-on-chip, and so on) poses a significant barrier to use of these parts in space flight applications. While the unique capabilities conferred by commercial technologies have motivated development of test methods for such parts, these methods are expensive, time-consuming, and in some cases may even alter the radiation response of the part [1], [2]. These difficulties have provided strong motivation for developing test facilities with more penetrating, higher-energy ion beams (see Fig. 1).

The new single-event effect test facility (SEETF) at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL) delivers highly energetic and penetrating heavy-ion beams (see Table I). [3] Such ion beams make possible testing of many commercial parts without delidding or other significant modification to the part. In addition, the extended energy range at NSCL makes it possible to reproduce 99% of the space radiation spectrum in linear energy transfer (LET) and energy for LET > 3 MeV $\cdot$ cm^2/mg (see Fig. 2). Moreover, the high ion energy means that testing can be done in air, rather than in vacuum, simplifying issues such as part cooling and access.

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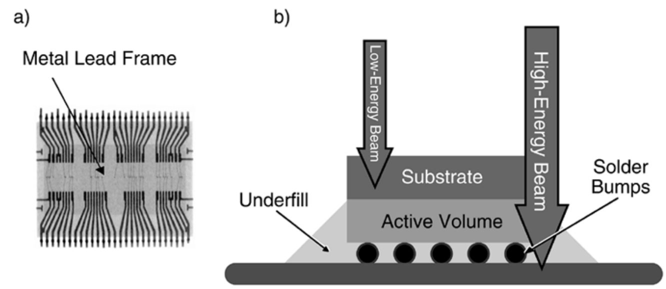

Fig. 1. High-energy ion beams can penetrate the thick overburdens associated with commercial microchips, e.g., (a) metal lead frames or (b) flip-chip packages.

TABLE I
AVAILABLE IONS, RANGES, AND LETS

Ion	Facility	Max. Energy (MeV/amu)	LET in Si (MeV•cm^2/mg)	Range in Si (μm)	Bragg-Peak LET in Si
Ar-36	NSCL	143	1.50	8860	18
Kr-78	NSCL	121	6.08	4440	40
Xe-136	NSCL	131	14.1	3070	69
Bi-209	NSCL	72	42	1100	100

Here we report on the performance of this facility during its first post-upgrade SEE runs: in February 2004 (with 9574-MeV Kr ions) and two runs in May 2004 (with 9574-MeV Kr and 15048-MeV Bi ions). Typical runs involve only a single ion, since switching ions requires a 24-hour tuning time. We also report results on irradiation of two 256 K SRAMs (Matra HM65656 and IDT71256). These parts were chosen because they represent technologies that have been thoroughly characterized, and as such, they are good candidates for benchmarking the performance of the facility. The HM65656 was irradiated previously at other SEE test facilities, including Brookhaven and the Tandem Accelerator Superconducting Cyclotron (TASCC). This facilitates comparison for consistency of cross sections from SEETF and these other facilities.

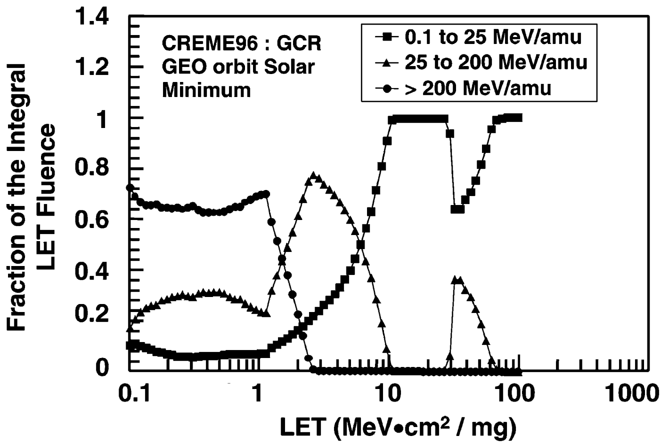

Fig. 2. Addition of the high-energy ions (with 60–143 MeV/nucleon) at NSCL fills important gaps and allows simulation of $\sim 99\%$ of the space radiation LET-energy phase space for LET > 3 MeV $\cdot$ cm^2/mg.

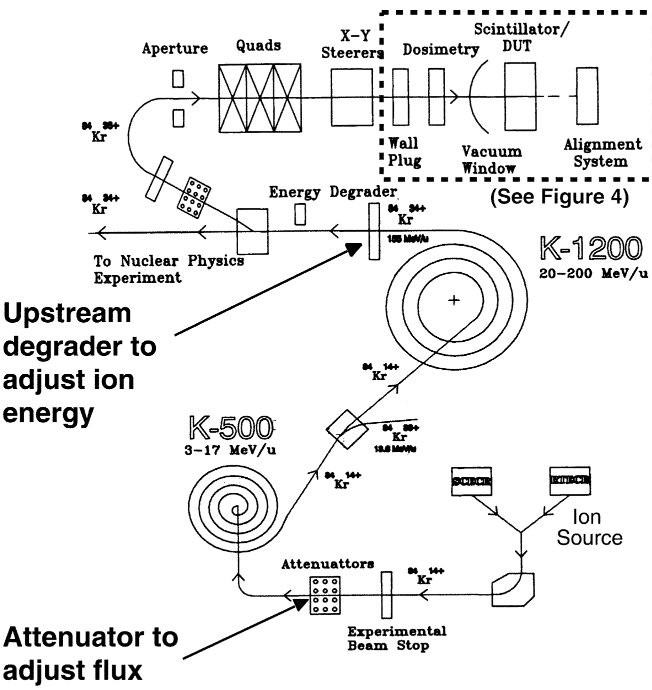

Fig. 3. Schematic of the main features of the accelerator and beam optics and the SEETF beam line (dashed box). Fig. 4 shows an expanded version of the main elements within the SEETF experimental area (inside dashed rectangle.).

II. SEETF Operation

The NSCL accelerator (see Fig. 3) consists of two coupled cyclotrons (a K500 and a K1200). Attenuation to the desired flux is done upstream of the accelerators to avoid beam detuning at the target. The synchronous operation of the cyclotrons and beam steering optics ensures uniformity of the ion, energy, and charge state. Beam energy degradation, if desired, can be done using either the degrading foils just downstream of the K1200 or with the degrading foil in the SEETF vault. The first option allows tuning of beam optics downstream of the degraders to ensure uniform beam energy at the target.

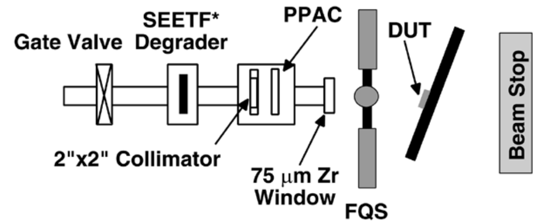

Fig. 4. Main elements inside the SEETF experimental vault.

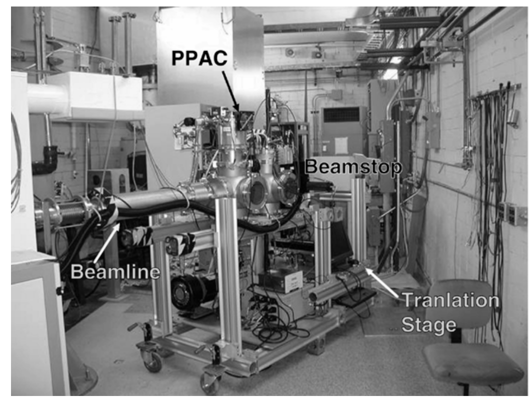

Fig. 5. SEETF experimental vault.

Fig. 6. Photograph of the user room.

As the ions reach the SEETF (see Fig. 4), they pass through a gate valve (which can be opened only when the vault is secured) and into the SEETF beam line.

The SEETF beam line includes two systems for measuring beam uniformity and dosimetry. For fluxes less than 4×10^2 cm^{-2}s^{-1}, the parallel plate avalanche counter (PPAC) provides detailed positions in the plane perpendicular to the beam axis (the X–Y plane) for individual ion strikes. The second dosimetry system, a four-quadrant thin scintillator (FQS) measurement system, provides detailed dosimetry and rudimentary beam-uniformity information for beam fluxes up to $\sim 1.5\times10^5$ cm^{-2}s^{-1} over the 5 cm $\times$ 5 cm beam spot. Dosimetry is accurate to about 10%. Downstream of the FQS, the ions strike the device under test (DUT). The target positioning stage provides translation in the X–Y plane and rotation about the vertical axis (in $\theta\theta$). Fig. 5 shows the experimental area in the SEETF vault. Fig. 6 shows a picture of the user control room.

III. Facility Control

The SEETF is controlled from the user control room (Fig. 6) or the SEETF experimental vault (Fig. 5) by two computer systems. A Windows-based system controls target positioning, the downstream degrader, and other aspects pertaining to the SEETF beam line elements. The Windows system also starts and stops irradiation of the part.

Data acquisition is handled by a Linux-based system, which controls the beam-monitoring equipment and display, storage of facility data for the run, and so on. It also allows the user to save the data at the end of the run.

Control of the beam (including flux, quality, and tuning) is exercised by the accelerator operators. Users may request changes by calling the operator in the control room. Flux can usually be incremented or decremented in a few minutes. Tuning for beam uniformity may be more involved but is usually completed within 15 to 30 minutes. Beam energy degradation to increase ion LET can involve a retune to ensure uniform energy.

IV. Beam Quality and Dosimetry

During the February and May 2004 beam runs, both the PPAC and the FQS were used to monitor the beam quality and measure dosimetry. Because the PPAC provides more detailed information on uniformity over the 5 cm $\times$ 5 cm beam spot size, initial runs were conducted at low flux with the PPAC in the beam line. In subsequent runs, the flux was raised by decreasing the attenuation upstream of the K500 cyclotron, and the PPAC was removed. This produces a beam profile with uniformity comparable to the low-flux, high-attenuation beam. The FQS provides information sufficient to indicate any major changes in uniformity. The procedure of beginning with low flux in order to use the PPAC and then transitioning to the FQS was followed whenever the beam was retuned.

Fig. 7 illustrates the beam quality characteristic of the February and May 2004 runs. The upper left plot shows the PPAC readout (in the laboratory, fluence is color-coded as red = high, blue = low). The upper right and lower left plots show, respectively, histograms of counts in the PPAC within a central slice along the Y or X axis. The lower right plot shows counts in each quadrant of the FQS.

Beam quality remained uniform ($> 85\%$ uniformity) over the 5 cm $\times$ 5 cm beam spot. Fluxes ranged from 10^2 to 10^5, and could be changed using the upstream attenuator in less than 30 minutes (< 5 minutes was typical). During the February 2004 run, the upstream degraders were used to change the energy of the Kr ion beam, bumping the LET from 6.3 MeV $\cdot$ cm^2/mg to 8.7 MeV $\cdot$ cm^2/mg. The beam optics required less than 2 hours for retuning after the change.

V. Cross-Facility Comparison

To assess SEETF data quality in relation to that from other facilities, we irradiated a Matra HM65656 256 K SRAM, dubbed DUT #30, which had been irradiated previously at the Brookhaven SEUTF and TASCC. Fig. 8 indicates the excellent agreement between facilities.

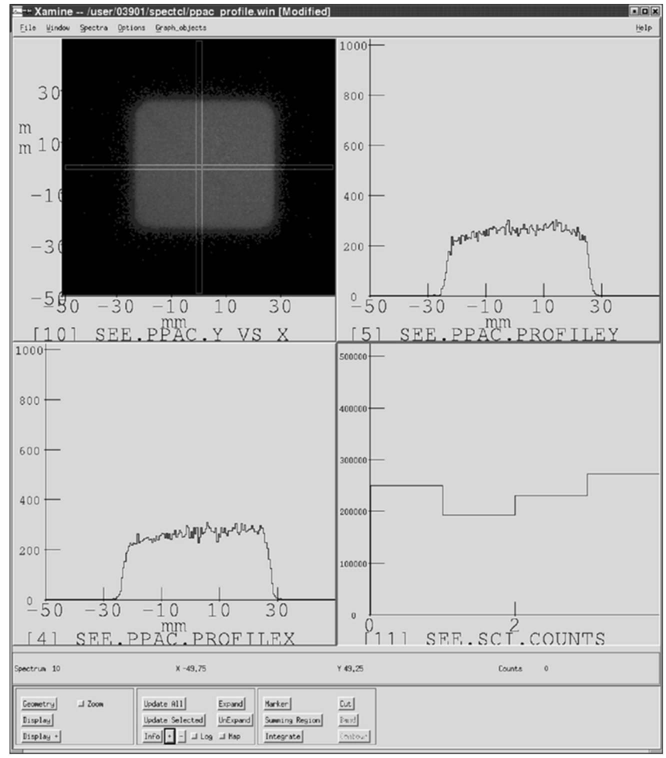

Fig. 7. Sample readout of the PPAC and FQS. Upper left: gray-scale representation of PPAC readout indicates flux uniformity. Upper right and lower left: PPAC counts within a central slice in the Y and X directions, respectively. Lower right: Counts in the FQS.

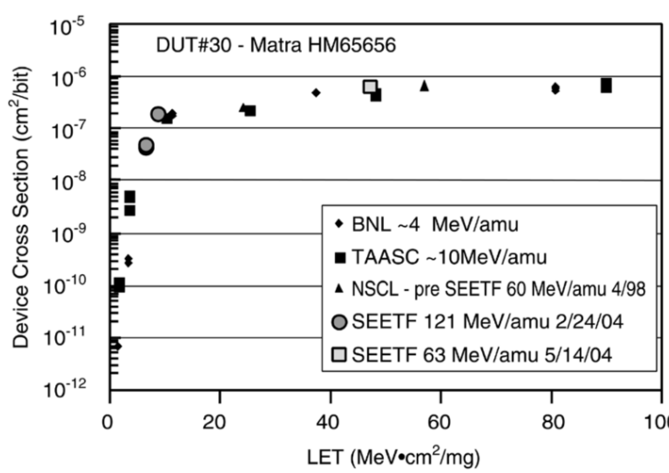

Fig. 8. The same Matra HM65656 irradiated at TASCC, NSCL, Michigan State University (pre-upgrade) and Brookhaven yields consistent cross section versus LET curves over beam energies spanning a factor of 40.

VI. Ion LET Determination

Determining ion LET after the beam has traversed DUT overlayers can be challenging. Monte Carlo transport codes like SRIM [4] or empirical fits to data such as LISE [5] can be effective for overlayers of known thickness and composition. However, assumptions about overlayer compositions are risky, especially for plastic-encapsulated parts. Table II shows results for several packaged and delidded Matra 65656 and IDT71256 SRAMs for the degraded and undegraded Kr beams. The two orders of magnitude drop in cross section exhibited by the

TABLE II
SEU CROSS SECTIONS FOR PRIMARY AND DEGRADED BEAMS

Part	Packaging	Incident Energy (MeV)	LET @ die surface (MeV•cm²/mg)	Average Cross Section (cm²)
IDT71256	Lidded Plastic	9574	>6.3	2.01×10^{-3}
IDT71256	Delidded	9574	6.3	1.08×10^{-3}
IDT71256	Lidded Plastic	5953	>8.7	6.92×10^{-5}
IDT71256	Delidded	5953	8.7	5.15×10^{-3}
M65656	Delidded	5953	8.7	4.89×10^{-2}
M65656	Lidded	5953	>8.7	1.35×10^{-1}
M65656	Delidded	9574	6.3	1.25×10^{-2}
M65656	Lidded	9574	>6.3	1.61×10^{-2}

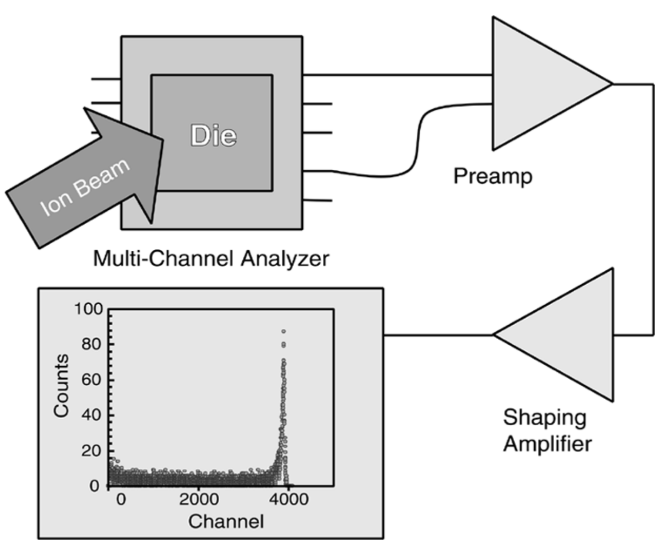

Fig. 9. Charge collection spectroscopy setup.

plastic packaged IDT71256 versus the delidded version for the degraded Kr beam indicates that the ions are "ranging out" in the package before they reach the sensitive volume in the silicon. This indicates that the plastic packaging was denser than would be predicted for a typical pure polymer. This is not surprising, since many plastics have high glass content for thermal, structural, or other reasons. In contrast, the results for the packaged and delidded hermetic IDT71256 and both the plastic and hermetic M65656 are consistent with expectations for the cross section versus LET curve. (Note: LET is not calculated for the packaged parts, since this would require details of package composition that were not available.)

An alternative to estimating LET is to measure it using charge collection spectroscopy [6]. This technique uses a delidded (but not necessarily functional) part identical to the DUT and an ion beam of known LET incident on the bare die to measure the scaling relation between charge collected and LET (see Fig. 9.) The charge collected for the same peak for a packaged device then determines the LET of the ions after they have traversed the device overlayers (see Fig. 10).

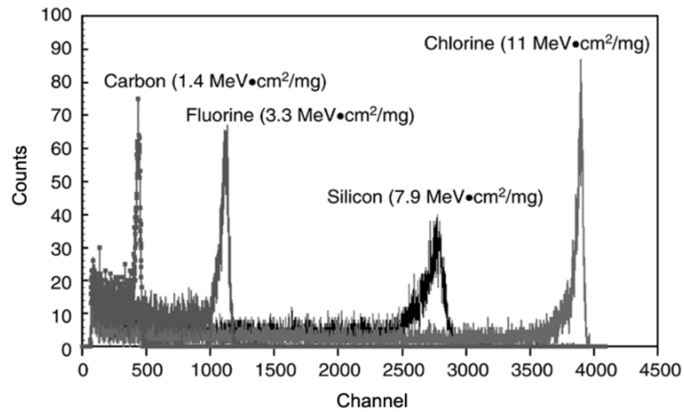

Fig. 10. Charge-collection peaks for several ions at Brookhaven.

VII. Complement to Other Facilities

The SEETF at NSCL offers highly penetrating energetic ion beams in combination with the dosimetry, targeting, and other facilities needed to produce high-quality SEE data. However, the facility cannot supplant existing heavy-ion SEE laboratories. The cost of beam time ($2,300/hour to $2,700/hour) is significantly higher than that at lower energy facilities such as the Brookhaven SEUTF, Berkeley, and Texas A&M (although if the metric is cost per MeV per amu or cost per micron of range, the SEETF is a bargain). The time available for SEE studies is limited (< 600 hours per year). Perhaps the most significant limitation of the facility is that unless the user is willing to pay a significant premium for beam tuning, SEE runs will generally have to be conducted with a single ion and therefore over a limited LET range.

The capabilities of the SEETF complement those of other heavy-ion facilities. The longer ranges of NSCL's ions will be invaluable for some testing requirements, e.g., when several devices need to be screened for single-event latchup and other serious error modes, with the best performers being subjected to more thorough testing. Other studies where high-energy ions would be invaluable include investigation of track structure effects and of energy dependence of susceptibility to some SEE mechanisms (e.g., single-event gate rupture [7]).

VIII. Future Development

Because the SEETF is a new facility, it is still subject to improvement. The highest priorities for near-term development are intended to increase the range of LETs and penetration depths available. One upgrade involves installing a translation stage to move the target along the beam axis, reducing the air gap and thereby slightly increasing the energy and range of the ions incident on the DUT. Such capability could be important for thick devices when ion penetration is marginal. This capability, however, also requires refinement of the targeting system. During the May 2004 run, an extension was mounted on the target assembly to place the part as close to the beam exit port as possible. The DUT was then positioned by hand at the center of the beam aperture.

Another project involves adding rotational capability to the downstream degrader foil, giving a nearly continuous range of effective degrader thicknesses (and LETs). In conjunction with this capability, an ion energy measurement system for degraded beams will allow the user to measure the energy spectrum of degraded beams and estimate systematic errors introduced by beam straggling.

IX. Conclusion

With the completion of the inaugural run of the SEETF at Michigan State University, the radiation community has a powerful new tool, both for penetrating novel package technologies and for the simulation of high-energy ions in the space environment. The results of these runs indicate both the strengths of this new facility-its high energy, penetrating power, and ease of use-as well as its weaknesses-the difficulty in switching ions to map out a full cross section versus LET curve. These characteristics suggest that the MSU facility represents an excellent complement to other existing test facilities. Questions about the SEETF should be directed to Ray Ladbury at NASA Goddard Space Flight Center.

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